What the PV Specialists Might Like to Know About Solid-State Lighting

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http://lighting.sandia.gov

* Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U. S. Department of Energy under contract DE-ACO4-94AL85000.

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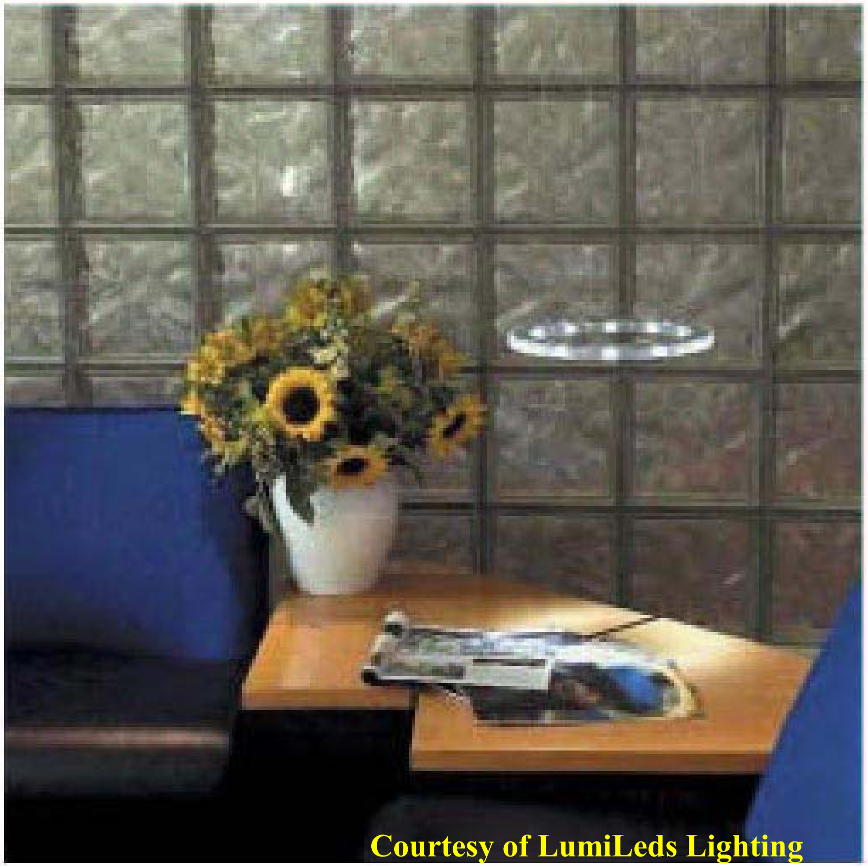
Outline

- Introduction to Solid-State Lighting
- LED/OLED Technology Drivers
- LED/OLED Market Drivers
- Lighting Market



Courtesy of LumiLeds Lighting

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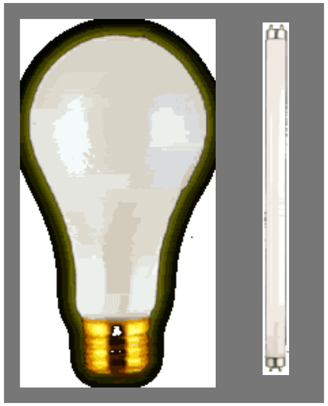
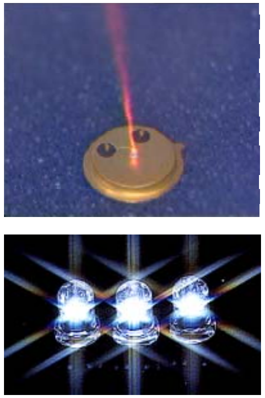
Solid-State Lighting

Fire

Candles and Lamps



Bulbs and Tubes



Semiconductors

Solid-state lighting promises to revolutionize the way we illuminate our public spaces, our work environments, and our homes while reducing energy consumption and creating a vibrant new industry.

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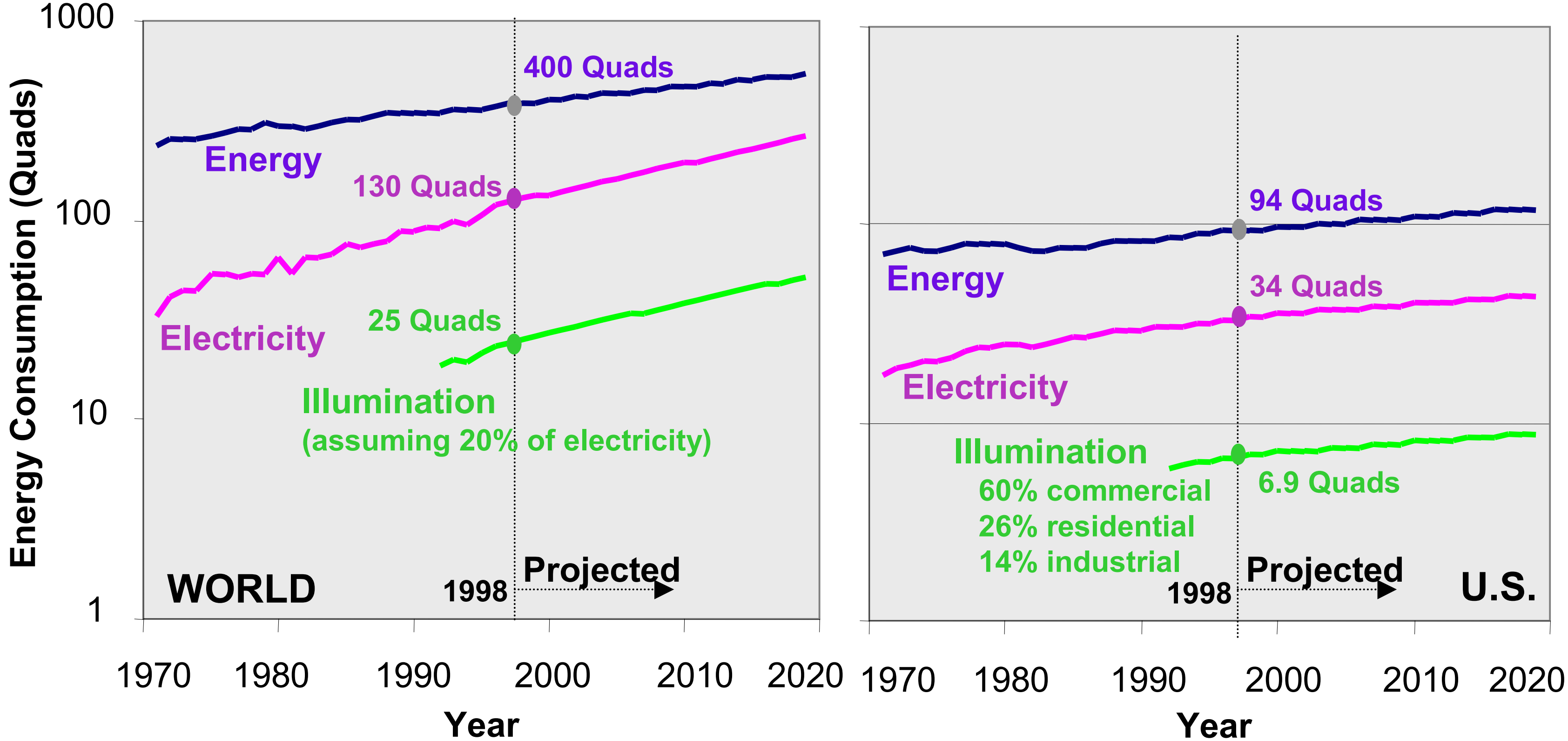
Lighting Energy Consumption



~20% of U.S electricity consumption is for general illumination

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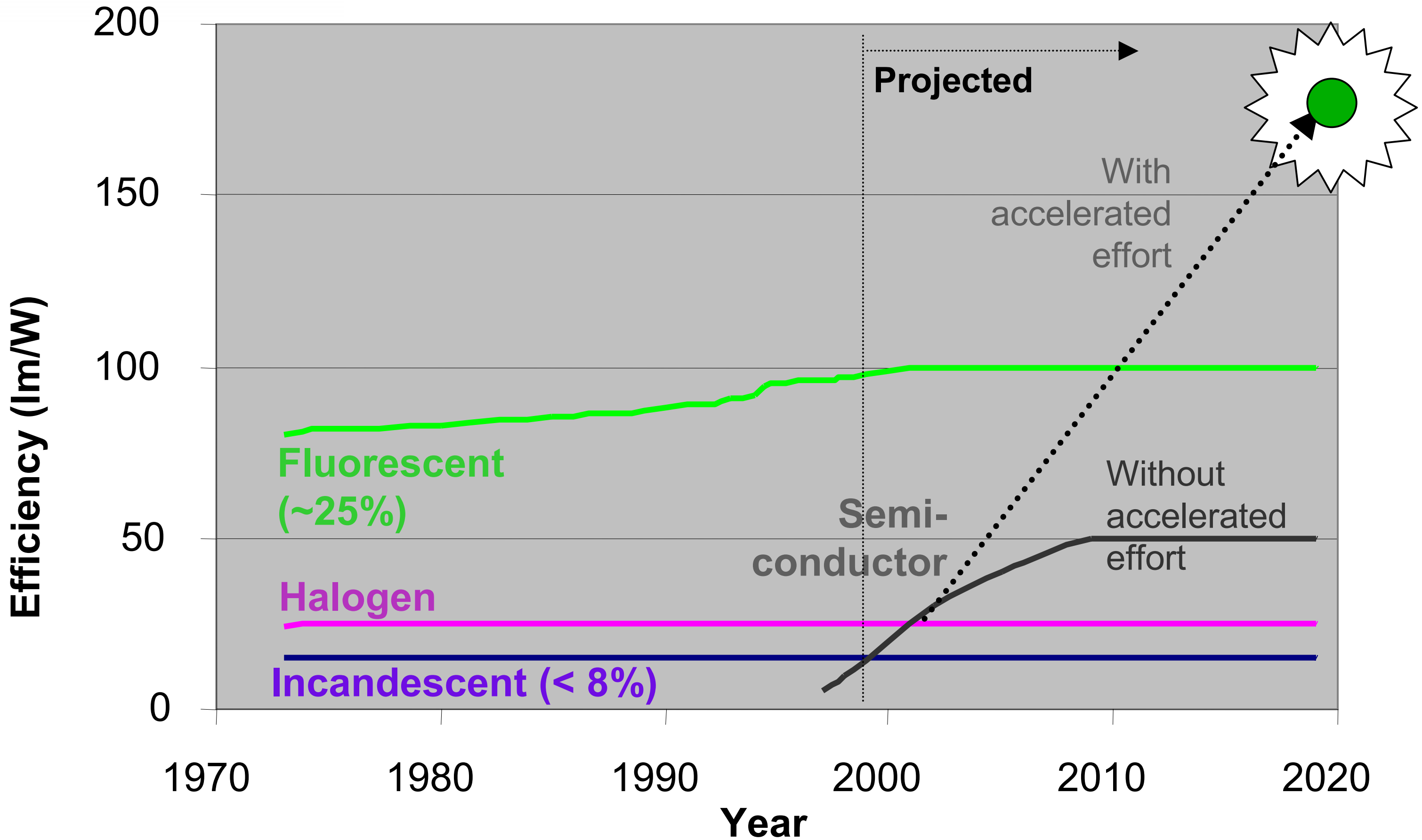
Lighting Efficiencies



Energy Efficiency: Solid-state lighting is potentially **10X and 2X more efficient** than incandescent and fluorescent lamps, respectively.

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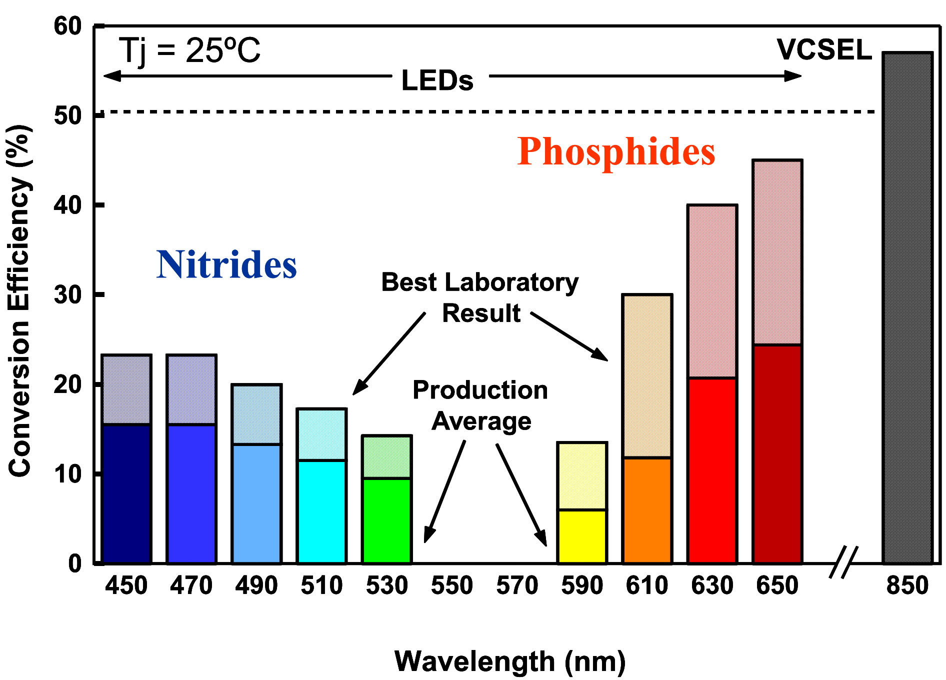
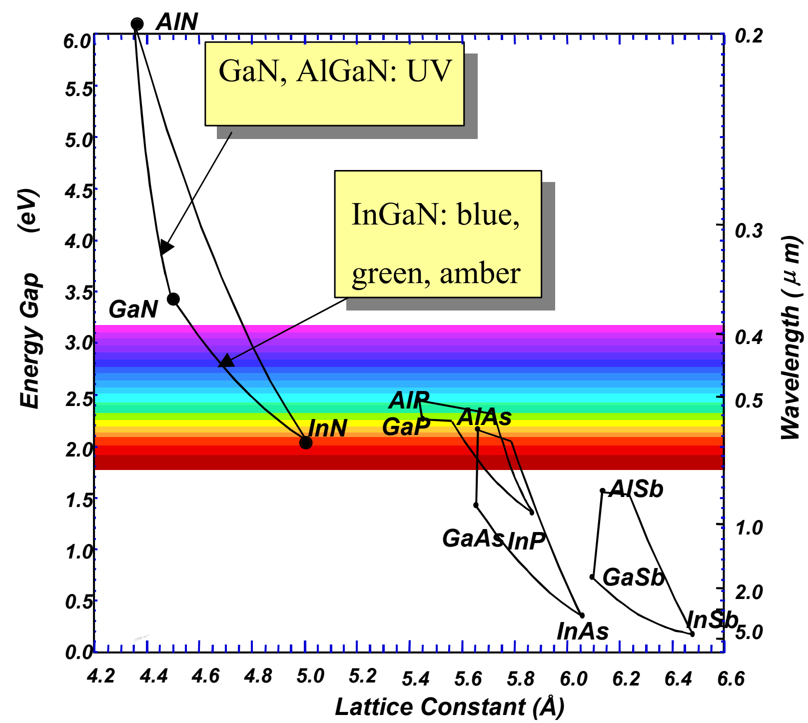
High-Brightness LEDs





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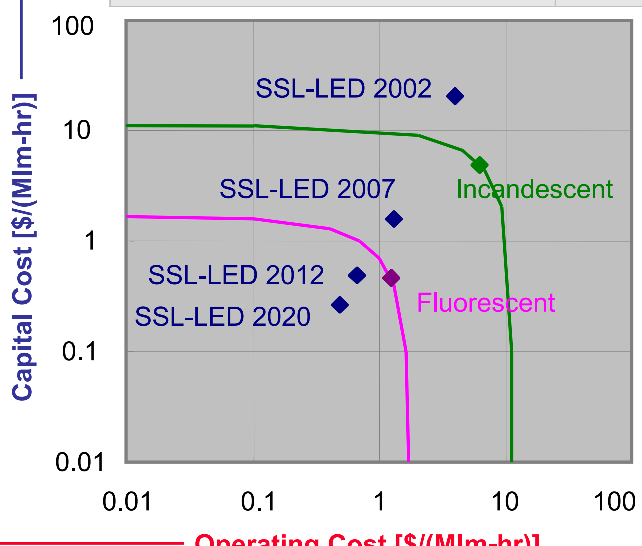
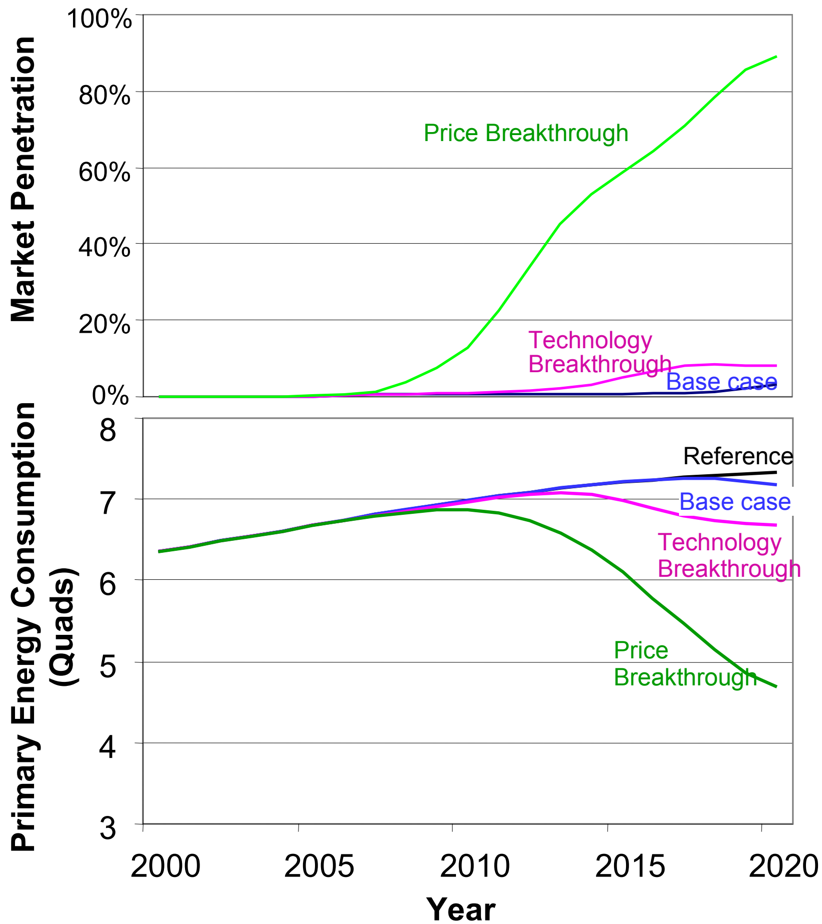
LED-SSL Roadmap Targets

TECHNOLOGY	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incande-scent	Fluore-scent
Luminous Efficacy (lm/W)	25	75	150	200	16	85
Lifetime (khr)	20	>20	>100	>100	1	10
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400
Input Power (W/lamp)	1	2.7	6.7	7.5	75	40
Lumens Cost ($/klm)	200	20	<5	<2	0.4	1.5
Lamp Cost ($/lamp)	5	4	<5	<3	0.5	5
Color Rendering Index (CRI)	75	80	>80	>80	95	75
Lighting Markets Penetrated	Low-flux	Incande-scent	Fluore-scent	All		



- **Targets mostly based on raw economic performance (not human factors)**
  - **Incandescence in 5 years**
  - **Fluorescence in 10 years**
- **Cost of Ownership**
  = Operating Cost + Capital Cost

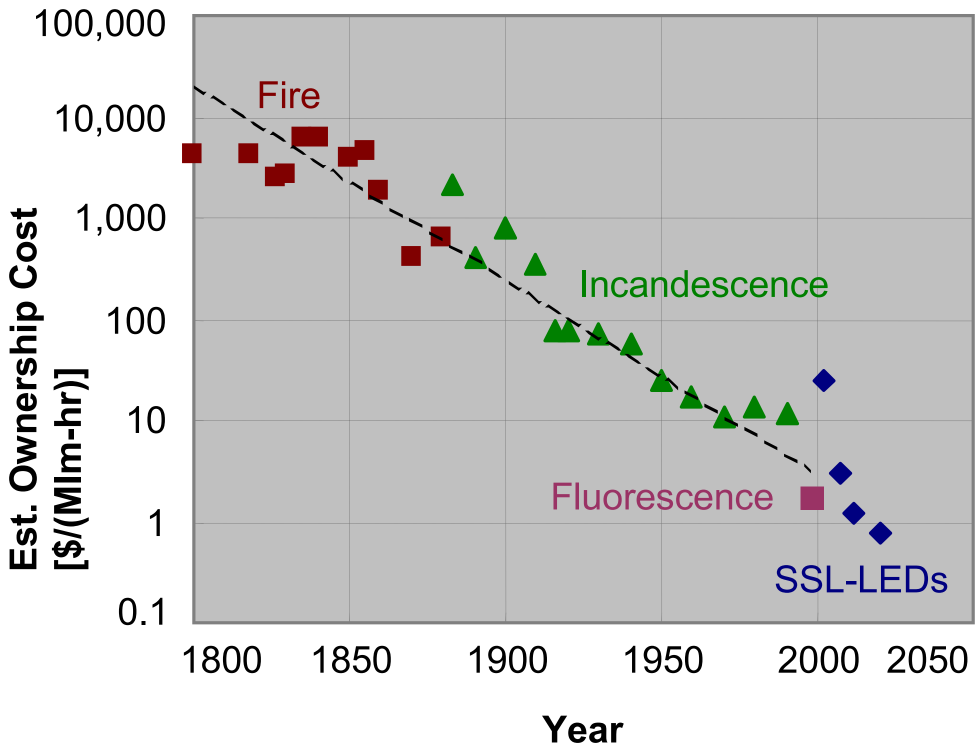
Impact of SSL on Energy Consumption



M. Kendall and M. Scholand, "Energy Savings Potential of SSL in General Lighting Applications" (U.S. DOE-OBT study by Arthur D. Little, 2001).

- **Base:**
  - **Approximately the R. Haitz "evolutionary" scenario proposed in April 2000**
- **Technology Breakthrough:**
  - **Approximately the R. Haitz "revolutionary" scenario proposed in April 2000**
- **Price Breakthrough:**
  - **Approximately the U.S. SSL Roadmap scenario proposed in August 2002**

Economic History of Light



Data for Fire and Incandescence modified from W.D. Nordhaus, in T.F. Breshnahan and R.J. Gordon, Eds., The Economics of New Goods (U of Chicago Press, 1997) pp. 29-70.
Data for SSL-LEDs taken from 2002 U.S. SSL Roadmap.

- **Nordhaus' observation**
  - **10x decrease in cost of light per 50 years**
- **Decrease is:**
  - **¾ due to increase in luminous efficacy**
  - **¼ due to decrease in cost of fuel**
- **SSL LED goals follow historical extrapolation**

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Warning

The following two viewgraphs are a paid political advertisement.

Sandia Solid-State Lighting Project

Illumination through semiconductor science

- Sandia National Laboratories is a DOE national security laboratory with a mission of *helping our nation secure a peaceful and secure world through technology.*
- Sandia's SSL project is internally funded (around $7M over 3 years) with around 25 contributors working on solid-state physics, MOCVD, low-defect substrates, LEDs, phosphors, and encapsulation.
- Sandia's SSL technology infrastructure developed for a variety of national security missions.
- http://lighting.sandia.gov

LED-SSL Roadmap Challenges

1 <u>Substrates, Buffers and Epitaxy</u>
- *1.1 Substrates*
- *1.2 Buffers*
- *1.3 Epitaxy Tools*
- *1.4 Epitaxy Processes*

2 <u>Physics, Processing and Devices</u>
- *2.1 Semiconductor Physics*
- *2.2 Device Processing*
- *2.3 LEDs and Integrated LEDs*
- *2.4 Directional Emitters*

3 <u>Lamps, Luminaires and Systems</u>
- *3.1 Phosphors and Encapsulants*
- 3.2 Lamps and Electronics
- 3.3 Luminaires
- 3.4 Lighting Systems

Roadmap divided into 12 technical areas. Challenges and targets were identified in each technical area.

Example: Cost, power, temperature targets established for chip and package.

Sandia National Laboratories is working on topics in *italics*.

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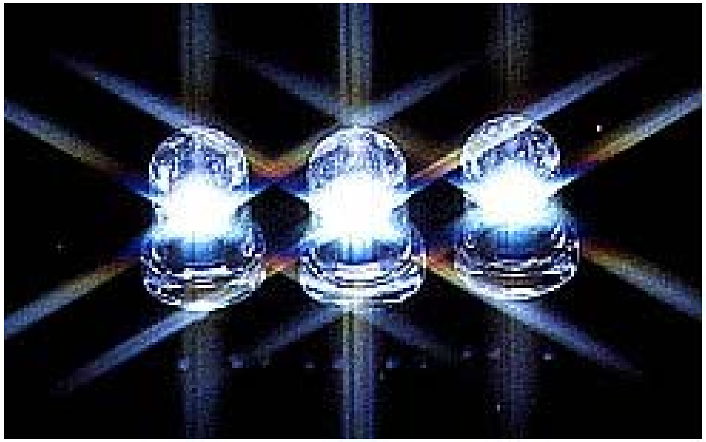
LED-SSL and PV Technology Comparison

LEDs are both "easier" and "more difficult" than PV.

- Engineering of electron-hole confinement for high radiative recombination efficiency is easier than engineering of photon absorption for high IQE
- LEDs can more easily be driven to higher current densities than sunlight can be concentrated in PV
- LEDs typically require a higher level of technical sophistication in growth technology.
- Nitride semiconductors are particularly difficult and unlike any other III-V semiconductors.



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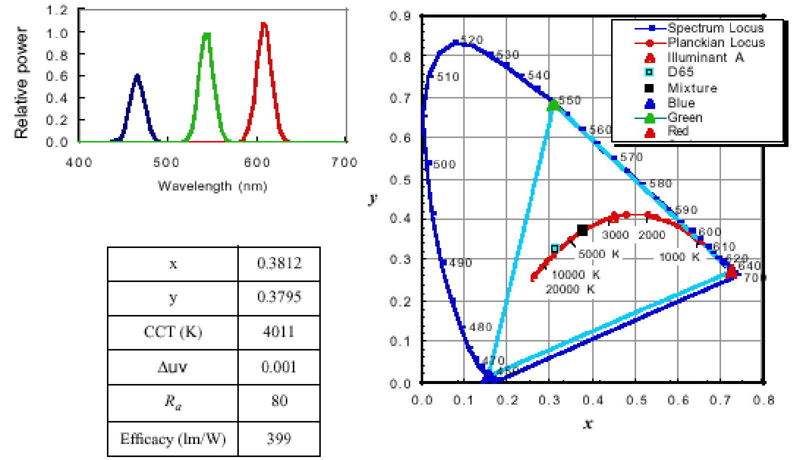
LED-SSL Cost Targets

$$\frac{lm}{W} = \eta_{ext} \frac{683 \cdot \int_{380}^{760} V(\lambda) I(\lambda) d\lambda}{\int_{0}^{\infty} I(\lambda) d\lambda} = 393 \cdot \eta_{ext}$$

$$\frac{lm}{A} = \eta_{ext} \frac{683 \cdot \int_{380}^{760} V(\lambda) I(\lambda) d\lambda}{\int_{0}^{\infty} I(\lambda) S(\lambda) d\lambda} = 884 \cdot \eta_{ext}$$

$$\frac{\$}{cm2} = \left(\frac{\$}{klm}\right)\left(\frac{lm}{A}\right)\left(\frac{kA}{cm2}\right)$$



x	0.3812
y	0.3795
CCT (K)	4011
Δuv	0.001
R_a	80
Efficacy (lm/W)	399

Figure 3.8. The effect of optimizing the wavelengths of a three-chip white-light LED. The chromaticity coordinates (x, y) for the white light is shown as the solid square near 4,000 K. Because of the CRI, $R_a \sim 80$, this is an example of example of white light with good color rendering.

\$1/klm cost target corresponds to die cost around \$20/cm^2

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OLED SSL and PV Comparison

- OLED is a broad-area diffuse source rather than a high-brightness point source like LEDs. Provides new concepts for illumination (luminous ceilings and walls).
- Potentially low-cost materials and processing. Nevertheless, manufacturing cost goals ($\$20/m^2$) are ambitious.
- Very new technology with unknown difficulties.
- Reliability will be a major concern. Extremely moisture sensitive.

True or False:

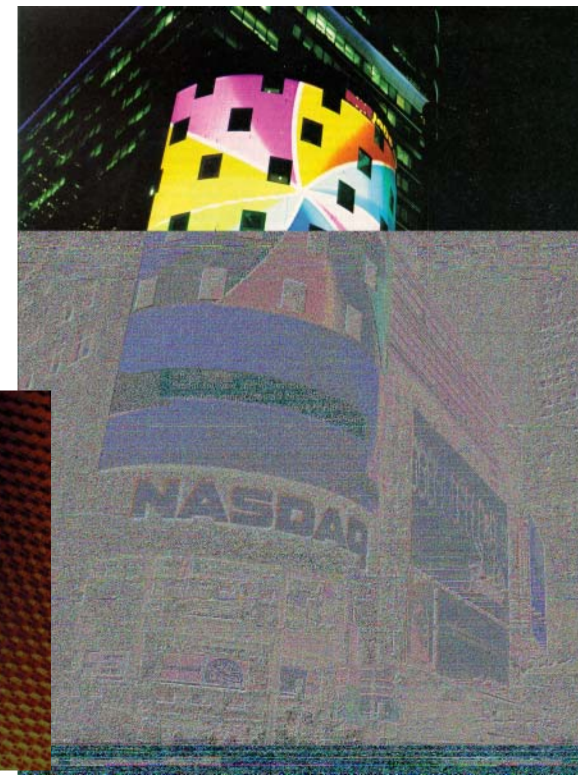
"OLED is to LED" as "Thin-Film is to c-Si"

HB-LED Market Drivers

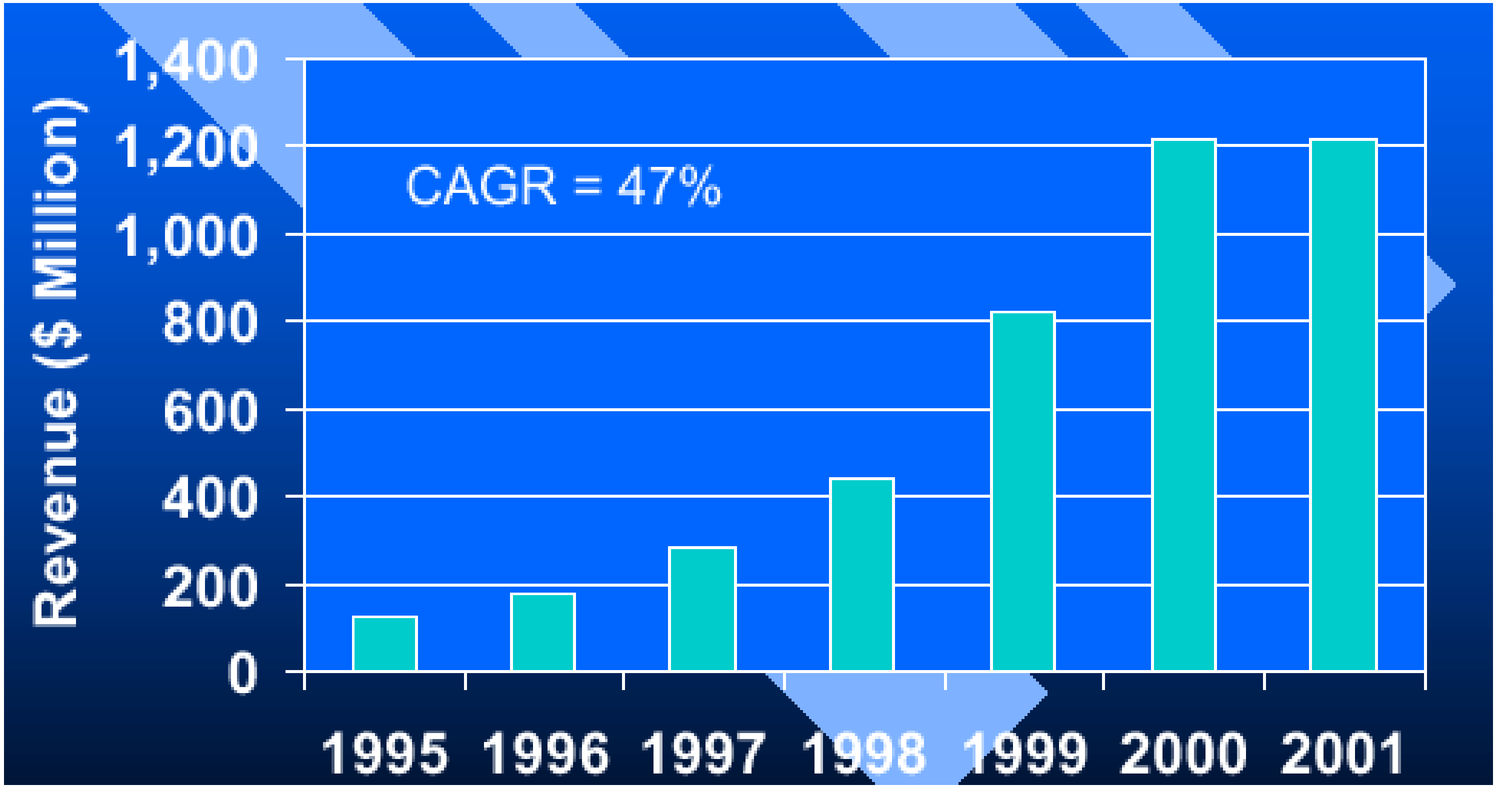

The Gewandhaus concert hall, Leipzig,

High-brightness LEDs have very strong high-value interim markets.

- Efficiency
- Lifetime
- Durability
- Styling
- Lifecycle cost



HB-LED Market



HB-LEDs reached $1.8B in 2002.

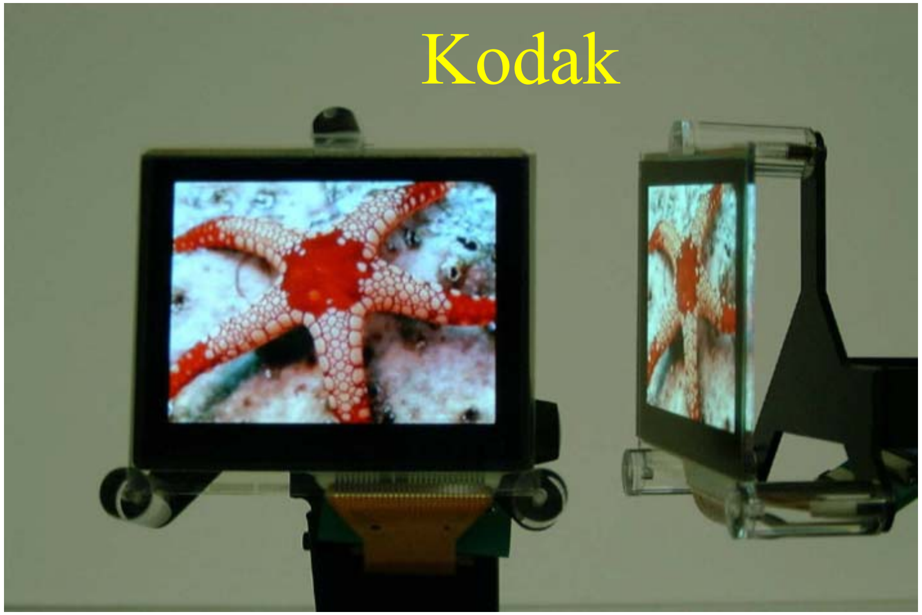
Source: Robert Steele, Strategies Unlimited.

HB-LED Industry

- InGaN HB-LED
  - 80% market held by Nichia, Toyoda Gosei, Cree
  - Very intense IP competition
  - Large investment by Taiwanese companies
  - Others: Uniroyal Optoelectronics, AXT, Kopin
- High-flux LEDs led by SSL joint ventures:
  - LumiLeds Lighting (Agilent and Phillips)
  - Osram Optoelectronics (Osram and Infineon)
  - GelCore (GE and Emcore)

OLED Market Driver

- **OLEDs are under intense development for displays**
  - ***greater brightness, faster response time, lower weight, and higher efficiency***
  - ***Around $100M in sales in 2001***
  - ***Global display market is $31B***



Lighting Market

- **Around $2.8B and $12B US and global sales for lighting source (incandescent, fluorescent, and HID).**
- **Global lighting industry dominated by 3 technologically sophisticated companies (GE Lighting, Osram/Sylvania, and Phillips).**
- **Luminaires have larger revenue – around $7.5B in US. Some luminaire manufacturers (Coopers Lighting) are larger than GE Lighting, but also a large number of small firms.**
- **Lighting is directly experienced by consumers – easier to market other values.**
- ***However,* tremendous customer inertia – i.e., slow acceptance of compact fluorescent lamps.**

My Reasons for Optimism

Compared to PV solar energy, solid-state lighting has the following advantages:

- **Technologically easier to make long-term cost targets (LEDs at $20/cm^2).**
- **High-value interim markets for both LEDs and OLEDs are both large and far from saturation.**
- **Consumers directly experience and purchase lighting – should be easier to differentiate new product in lighting than *green electrons* from solar-electric power.**

Acknowledgements

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